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Predicting tensile strength of friction stir welded AA6061 aluminium alloy joints by a mathematical model

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ABSTRACT

AA6061 aluminium alloy (Al–Mg–Si alloy) has gathered wide acceptance in the fabrication of light weight structures requiring a high strength-to weight ratio and good corrosion resistance. Compared to the fusion welding processes that are routinely used for joining structural aluminium alloys, friction stir welding (FSW) process is an emerging solid state joining process in which the material that is being welded does not melt and recast. This process uses a non-consumable tool to generate frictional heat in the abutting surfaces. The welding parameters such as tool rotational speed, welding speed, axial force etc., and tool pin profile play a major role in deciding the joint strength. An attempt has been made to develop a mathematical model to predict tensile strength of the friction stir welded AA6061 aluminium alloy by incorporating FSW process parameters. Four factors, five levels central composite design has been used to minimize number of experimental conditions. Response surface method (RSM) has been used to develop the model. Statistical tools such as analysis of variance (ANOVA), student's t-test, correlation co-efficient etc. have been used to validate the developed model. The developed mathematical model can be effectively used to predict the tensile strength of FSW joints at 95% confidence level.

1. Introduction

Heat treatable wrought aluminium–magnesium–silicon alloys conforming to AA6061 are of moderate strength and possess excellent welding characteristics over the high strength aluminium alloys [1]. Hence, alloys of this class are extensively employed in marine frames, pipelines, storage tanks and aircraft applications. Although Al–Mg–Si alloys are readily weldable, they suffer from severe softening in the heat affected zone (HAZ) because of reversion (dissolution) of Mg_2Si precipitates during weld thermal cycle [2]. This type of mechanical impairment presents a major problem in engineering design. It will be more appropriate to overcome or minimize the HAZ softening to improve mechanical properties of weldments [3].

Compared to many of the fusion welding processes that are routinely used for joining structural alloys, friction stir welding (FSW) is an emerging solid state joining process in which the material that is being welded does not melt and recast [4]. Friction stir welding (FSW) was invented at The Welding Institute (TWI), UK in 1991. Friction stir welding is a continuous, hot shear, autogenous process involving non-consumable rotating tool of harder material than the substrate material. Defect-free welds with good mechanical properties have been made in a variety of aluminium alloys, even those previously thought to be not weldable [5]. When alloys are friction stir welded, phase transformations that occur during the cooling cycle of the weld are of a solid state type. Due to the absence of parent metal melting, the new FSW process is observed to offer several advantages over fusion welding [6].

The formation of defect-free friction stir processed zone (FSP) regions is affected by the material flow behaviour under the action of rotating non-consumable tool [7]. However, the material flow behaviour is predominantly influenced by the FSW tool profiles, FSW tool dimensions and FSW process parameters [8,9]. Most of the published papers are focusing on the effect of FSW parameters and tool profiles on tensile properties and microstructure formation. Hence, an attempt has been made to develop a mathematical model to predict tensile strength of friction stir welded AA6061 aluminium alloy incorporating FSW parameters using statistical tools such as design of experiments, analysis of variance etc.

2. Experimental work

The rolled plates of 6 mm thickness, AA6061 aluminium alloy, were cut into the required size (300 mm × 150 mm) by power hacksaw cutting and milling. Square butt joint configuration (300 mm × 300 mm) was prepared to fabricate FSW joints. The initial joint configuration was obtained by securing the plates in position using mechanical clamps. The direction of welding was normal to the rolling direction. Single pass welding procedure was followed to fabricate the joints. Non-consum-

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Table 1a
Chemical composition (wt%) of base metal

Mg	Si	Fe	Cu	Cr	Mn	Zn	Ti	Al
0.9	0.62	0.33	0.28	0.17	0.06	0.02	0.02	Bal

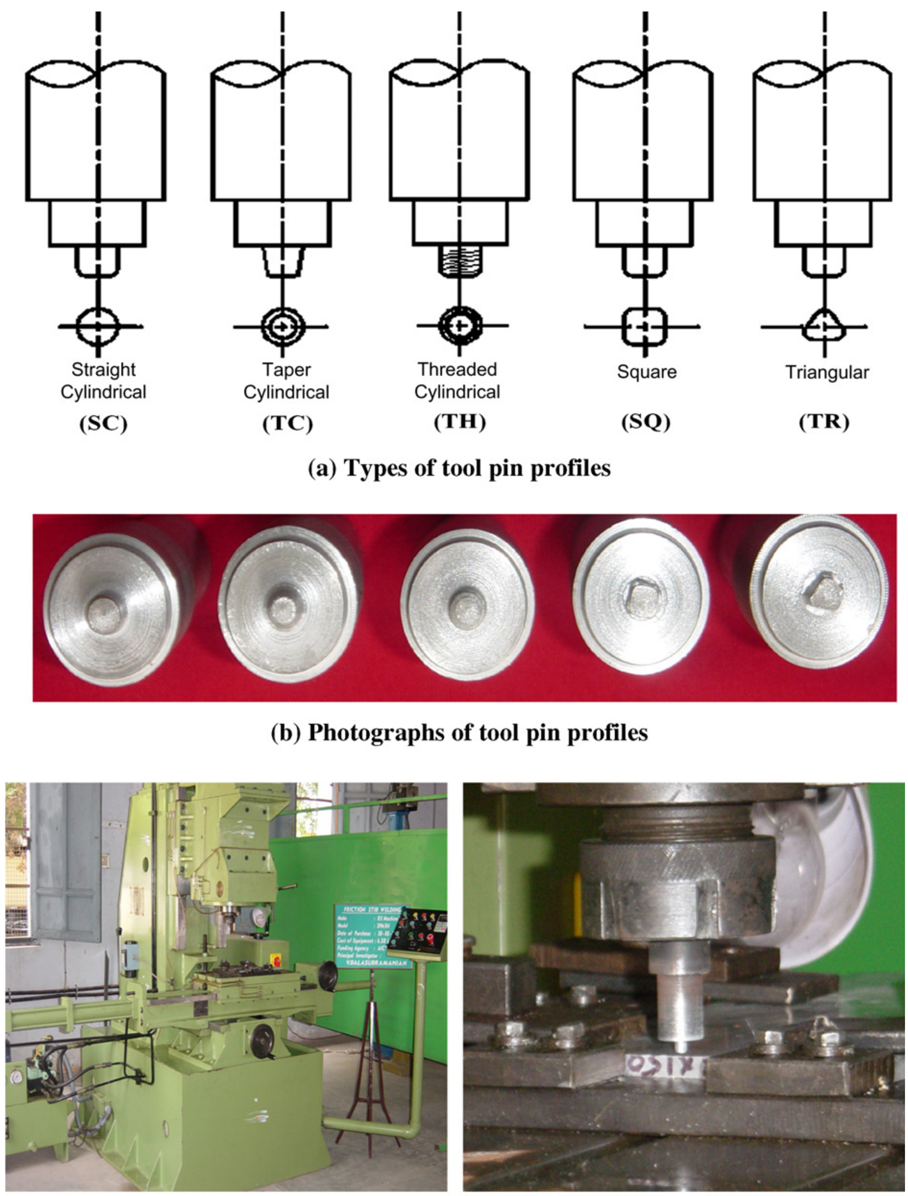
able tools, made of high carbon steel were used to fabricate the joints. The chemical composition and mechanical properties of base metal are presented in Table 1a and b. An indigenously designed and developed machine shown in Fig. 1c (15 HP; 3000 rpm; 25 kN) was used to fabricate the joints. Five different tool pin profiles, as shown in Fig. 1a and b were prepared from high carbon steel material and they were used to fabricate the joints but 18 mm shoulder diameter was maintained for all the pin profiles.

From the literature [4–9] and the previous work done in our laboratory [10,11], the predominant factors which are having greater influence on tensile strength of friction stir welded aluminium alloys were identified. They are: (i) tool pin profiles, (ii) tool rotational speed, (iii) welding (traverse) speed and (iv) axial (downward) force. Trial experiments were conducted to determine the working range of the above factors. Feasible limits of the parameters were chosen in such a way that the friction stir welded joints should be free from any visible external defects. The important factors that are influencing the tensile properties of FSW joints and their working range for AA6061 aluminium alloy are presented in Table 2.

Table 1b
Mechanical properties of base metal

Yield strength (MPa)	Ultimate tensile strength (MPa)	Elongation (%)	Reduction in cross sectional area (%)	Hardness (VHN)
302	334	18	12.24	105

Due to wide range of factors, it was decided to use four factors, five levels, central composite design matrix to optimise the experimental conditions. Table 3 shows the 31 sets of coded conditions used to form the design matrix. First 16 experimental conditions are derived from full factorial experimental design matrix ($2^4 = 16$). All the variables at the intermediate (0) level constitute the center points while the combinations of each process variable at either their lowest (−2) or highest (+2) with the other three variables of the intermediate levels constitute the star points. Thus the 31 experimental conditions allowed the estimation of the linear, quadratic and two-way interactive effects of the variables on the tensile strength of FSW joints. The method of designing such matrix is dealt elsewhere [12,13]. For the convenience of recording and processing experimental data, upper and lower levels of the factors have been coded as +2 and −2, respectively. The coded values of the any intermediate values can be calculated using the following relationship [14]:



(a) Types of tool pin profiles

(b) Photographs of tool pin profiles

(c) An indigenously developed friction stir welding machine and its close up view

Fig. 1. Types of tool pin profiles and experimental setup used in this investigation.

Table 2
Important factors and their levels

#	Parameter	Notation	Unit	Levels				
				(−2)	(−1)	(0)	(+1)	(+2)
1	Tool profile	P	–	SC	TH	SQ	TR	TC
2	Rotational speed	N	rpm	800	1000	1200	1400	1600
3	Welding speed	S	mm/s	0.25	0.75	1.25	1.75	2.25
4	Axial force	F	kN	5	6	7	8	9

SC: Straight Cylindrical pin profiled tool; TH: Threaded cylindrical pin profiled tool; SQ: Square pin profiled tool; TR: Triangular pin profiled tool; TC: Tapered Cylindrical pin profiled tool.

$$X_i = 2[2X - (X_{\max} + X_{\min})]/(X_{\max} - X_{\min}) \tag{1}$$

where X_i is the required coded value of a variable X; X is any value of the variable from $X_{\min}$ to $X_{\max}$; $X_{\min}$ is the lowest level of the variable; $X_{\max}$ is the highest level of the variable.

Table 3
Design matrix and experimental results

Experiment number	Factors				Tensile strength (MPa)
	P	N	S	F	
1	−1	−1	−1	−1	131
2	+1	−1	−1	−1	153
3	−1	+1	−1	−1	143
4	+1	+1	−1	−1	165
5	−1	−1	+1	−1	151
6	+1	−1	+1	−1	173
7	−1	+1	+1	−1	161
8	+1	+1	+1	−1	184
9	−1	−1	−1	+1	144
10	+1	−1	−1	+1	167
11	−1	+1	−1	+1	155
12	+1	+1	−1	+1	176
13	−1	−1	+1	+1	162
14	+1	−1	+1	+1	184
15	−1	+1	+1	+1	172
16	+1	+1	+1	+1	192
17	−2	0	0	0	118
18	+2	0	0	0	137
19	0	−2	0	0	145
20	0	+2	0	0	160
21	0	0	−2	0	140
22	0	0	+2	0	166
23	0	0	0	−2	150
24	0	0	0	+2	170
25	0	0	0	0	202
26	0	0	0	0	188
27	0	0	0	0	194
28	0	0	0	0	190
29	0	0	0	0	198
30	0	0	0	0	204
31	0	0	0	0	200

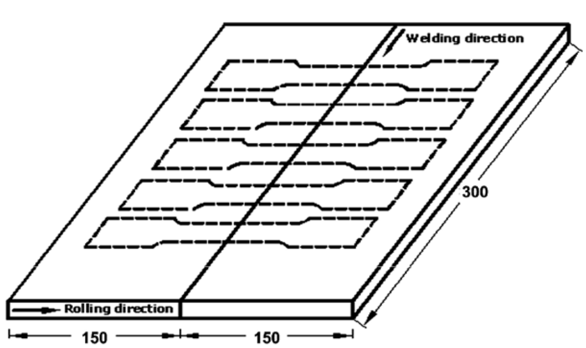


Fig. 2a. Scheme of welding with respect to rolling direction and extraction of tensile specimens.

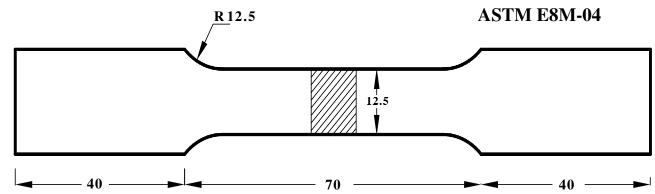


Fig. 2b. Dimensions of tensile specimen.

As prescribed by the design matrix *thirty-one joints* were fabricated. The welded joints were sliced (as shown in Fig. 2a) using a power hacksaw and then machined to the required dimensions as shown in Fig. 2b. Three tensile specimens were fabricated as per the American Society for Testing of Materials (ASTM E8M-04) standards to evaluate the tensile strength of the joints. Tensile strength of the FSW joints were evaluated by conducting test in Universal Testing Machine and the average of the three results is presented in Table 3.

3. Developing a mathematical model

The response function tensile strength (TS) of the joints is a function of tool profile (P), rotational speed (N), welding speed (S) and axial force (F) and it can be expressed as

$$\mathrm{TS} = f(P, N, S, F) \tag{2}$$

The second order polynomial (regression) equation used to represent the response surface 'Y' is given by

$$Y = b_0 + \sum b_i x_i + \sum b_{ii} x_i^2 + \sum b_{ij} x_i x_j \tag{3}$$

and for four factors, the selected polynomial could be expressed as

$$\begin{aligned}\mathrm{TS} = {} & b_0 + b_1(P) + b_2(N) + b_3(S) + b_4(F) + b_{11}(P^2) + b_{22}(N^2) \\ & + b_{33}(S^2) + b_{44}(F^2) + b_{12}(PN) + b_{13}(PS) + b_{14}(PF) \\ & + + b_{23}(NS) + b_{24}(NF) + b_{34}(SF)\end{aligned} \tag{4}$$

where b_0 is the average of responses and b_1, b_2,..., b_{23} are the co-efficients that depend on respective main and interaction effects of the parameters. The value of the co-efficients has been calculated using the following expressions [12,13]:

$$b_0 = 0.142857\left(\sum Y\right) - 0.035714 \sum\sum (X_{ii} Y) \tag{5}$$

$$b_i = 0.041667 \sum (X_i Y) \tag{6}$$

$$b_{ii} = 0.03125 \sum (X_{ii} Y) + 0.00372 \sum\sum (X_{ii} Y) - 0.035714\left(\sum Y\right) \tag{7}$$

$$b_{ij} = 0.0625 \sum (X_{ij} Y) \tag{8}$$

All the co-efficients were tested for their significance at 90% confidence level applying student's t-test using SPSS statistical software package. After determining the significant co-efficients, the final model was developed using only these co-efficients and the final mathematical model to predict tensile strength of FSW joints, developed by the above procedure is given below:

$$\begin{aligned}\mathrm{TS} = {} & \{196.29 + 6.88(P) + 4.46(N) + 9.13(S) + 5.96(F) \\ & - 13.46(P^2) - 7.20(N^2) - 9.46(S^2) - 12.58(F^2) \\ & - 1.81(PS) - 1.69(PF) - 2.56(SF)\}\mathrm{MPa}\end{aligned} \tag{9}$$

The adequacy of the developed model is tested using the analysis of variance technique (ANOVA). As per this technique, if the calculated value of the F_{ratio} of the developed model is less than the standard F_{ratio} (from F-table) value at a desired level of confidence (say 95%), then the model is said to be adequate within the confidence limit. ANOVA test results are presented in Table 4 for the model. From the table, it is understood that the developed mathematical model is found be adequate at 95% confidence level. Co-efficient

Table 4
ANOVA test results

Terms	AA6061
First order terms	
Sum of squares (SS)	4754.5
Degrees of freedom (dof)	4
Mean square (MS)	1188.6
Second order terms	
Sum of squares (SS)	9156.7
Degrees of freedom (dof)	10
Mean square (MS)	915.67
Error terms	
Sum of squares (SS)	221.714
Degrees of freedom (dof)	6
Mean square (MS)	36.95
Lack of fit	
Sum of squares (SS)	1478.9
Degrees of freedom (dof)	10
Mean square (MS)	147.89
F_{ratio} (calculated)	4.006
F_{ratio} (10,6,0.05)	4.06
Whether the model is adequate?	Yes

Table 5
Comparison between experimental and predicted values

Parameters	Experimental TS (MPa)	Estimated TS (MPa)	Variation (%)	r^2
P = SC; N = 1000; S = 0.75; F = 8	98	94.14	+3.86	0.91
P = TC; N = 1000; S = 1.25; F = 6	122	129.39	−7.39	
P = TH; N = 1200; S = 1.75; F = 7	175	177.43	−2.43	
P = SQ; N = 1400; S = 0.75; F = 5	112	107.60	+4.4	
P = TR; N = 800; S = 1.25; F = 8	150	143.68	+6.32	

of determination 'r^2' [14] is used to find how close the predicted and experimental values lie. The value of 'r^2' for the above-developed model is presented in Table 5, which indicates high correlation exist between experimental values and predicted values.

4. Discussion

Mathematical model developed in the preceding section was written in C program and the developed C program was used to estimate the tensile strength of friction stir welded AA6061 aluminium alloy joints for different combinations of FSW parameters. Predicted values are plotted as graphs and they are displayed in Figs. 3–5. The plotted graphs can be effectively used to understand the effect of FSW parameters such as tool rotational speed, welding speed, axial force and tool profile on tensile strength of friction stir welded AA6061 aluminium alloy joints.

4.1. Effect of tool rotational speed

The yield strength and tensile strength of all the joints are lower than that of the base material, irrespective of the rotational speeds used to fabricate the joints. Of the five rotational speeds used to fabricate AA6061 joints, the joint fabricated at a rotational speed of 1200 rpm yielded superior tensile properties. Fig. 3 reveals the effect of tool rotational speed on tensile strength of friction stir welded AA6061 aluminium alloy. At lower rotational speed (800 rpm) tensile strength of the FSW joints is lower. When the rotational speed is increased from 800 rpm, correspondingly the tensile strength also increased and reaches a maximum at 1200 rpm. If the rotational speed is increased above 1200 rpm, the tensile strength of the joint decreased. This trend is common in all the joints irrespective of tool pin profile.

The tensile properties and fracture locations of the joints are to a large extent, dependent on the rotational speed and other parameters. When the joints are associated with defects like pinhole, tunnel and cracks in the FSP region, the joints failed at the defective area and if the joints are defect free, the failure locations shifted to lowest hardness zone. Macro structure observations showed that the joints fabricated at lower rotational speeds (800, 1000 rpm) contained defects like pinhole or crack in FSP region and resulted in lower tensile properties. On the other hand, joints

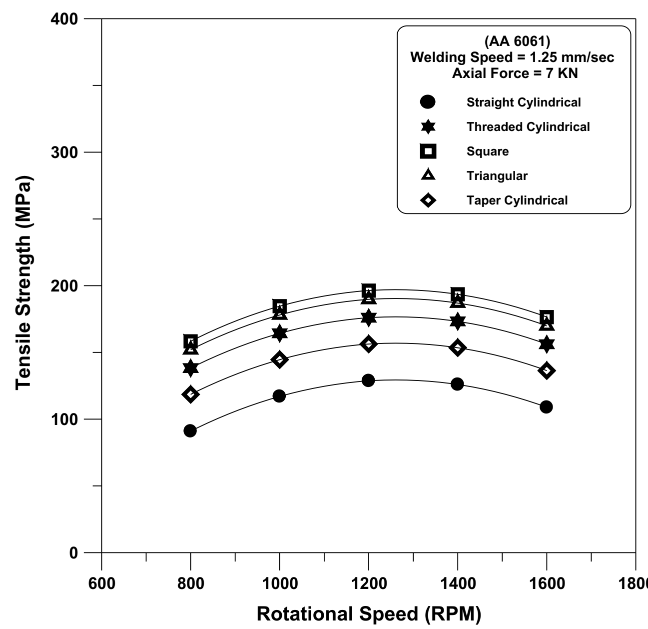


Fig. 3. Effect of tool rotational speed on tensile strength.

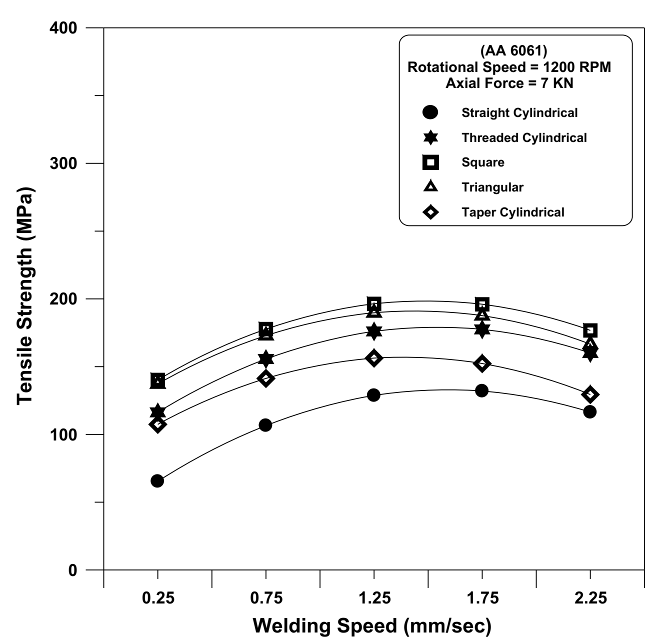


Fig. 4. Effect of welding speed on tensile strength.

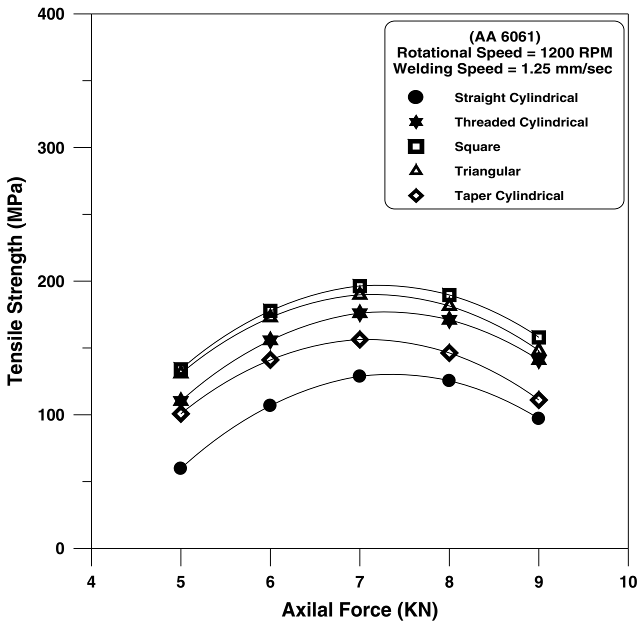


Fig. 5. Effect of axial force on tensile strength.

fabricated at higher rotational speeds (1400, 1600 rpm) contained large size defects and it appeared like tunnel [15]. As rotational speed increased, the heat input per unit length of the joint increased, resulting inferior tensile properties due to rise in temperature, which increases grain growth. Considerable increase in turbulence, which destroys the regular flow behavior available at lower speed, is also observed.

4.2. Effect of welding speed

The welding speed has a strong impact on productivity in streamlined production of friction stir welding of aluminium alloy sections. A significant increase in welding speed is achieved with high weld quality and excellent joint properties. The softened area is narrower for the higher welding speed than that for the lower welding speed. Thus, the tensile strength of as welded aluminium alloy has a proportional relationship with welding speed [16]. Higher welding speeds are associated with low heat inputs, which result in faster cooling rates of the welded joint. This can significantly reduce the extent of metallurgical transformations taking place during welding (such as solubilisation, re-precipitation and coarsening of precipitates) and hence the local strength of individual regions across the weld zone [17].

When the welding speed is slower than a certain critical value, the FSW can produce defect-free joints. When the welding speed is faster than the critical value, welding defects can be produced in the joints. The defects act as a crack initiation site during tensile test. Therefore, the tensile properties and fracture locations of the joints are determined by the welding speed [18].

Fig. 4 reveals the effect of welding speed on tensile strength of friction stir welded AA6061 aluminium alloy. At lower welding speed (0.25 mm/s) tensile strength of the FSW joints is lower. When the welding speed is increased from 0.25 mm/s, correspondingly the tensile strength also increased and reaches a maximum at 1.25 mm/s. If the welding speed is increased above 1.25 mm/s, the tensile strength of the joint decreased. This trend is common in all the joints irrespective of tool pin profile. Macro structure observations showed that the joints fabricated at lower welding speeds (0.25 mm/s and 0.75 mm/s) contained defects like pinhole or crack in FSP region and resulted in lower tensile properties. On the other hand, joints fabricated at higher welding speeds (1.75 mm/s and 2.25 mm/s) contained large size defects and it appeared like tunnel [19]. In general friction stir welding at higher welding speeds results in short exposure time in the weld area with insufficient heat and poor plastic flow of the metal and causes some voids like defects in the joints. It seems that these voids are formed due to poor consolidation of the metal interface when the tool travels at higher welding speeds. The reduced plasticity and rates of diffusion in the material may have resulted in a weak interface.

4.3. Effect of axial force

Fig. 5 reveals the effect of axial force on tensile strength of friction stir welded AA6061 aluminium alloy. At lower axial force (5 kN) tensile strength of the FSW joints is lower. When the axial force is increased from 5 kN, correspondingly the tensile strength also increased and reaches a maximum at 7 kN. If the axial force is further increased above 7 kN, the tensile strength of the joint decreased. This trend is common in all the joints irrespective of tool pin profile.

The heat input and temperature distribution during friction stir welding is due to frictional heat generation between the rotating tool shoulder and surface of the plate to be welded and in turn depends on co-efficient of friction. Apart from the properties of tool and plate material, the axial force decides the coefficient of friction. Hence axial force plays a significant role in friction stir welding process. The degree of material mixing and inter diffusion, the thickness of deformed aluminum lamellae, the material flow patterns highly depends on welding temperature, flow stress and axial force [20].

Oyuang and Kovacevic [21] observed that the axial force is directly responsible for the plunge depth of the tool pin in to the work piece and load characteristics associated with linear friction stir weld. When the axial force is relatively low, there is a tunnel found at the bottom. While with higher axial force, the weld is sound with full penetration. It shows that sufficient axial force is required to form good weld. This is because the temperature during friction stir welding defining the amount of plasticized metal and the temperature is greatly dependent on the axial force.

4.4. Effect of tool profile

The primary function of the non-consumable rotating tool pin is to stir the plasticized metal and move the same behind it to have good joint. Pin profile plays a crucial role in material flow and in turn regulates the welding speed of the FSW process. Friction stir welds are characterized by well defined weld nugget and flow contours, almost spherical in shape, these contours are dependent on the tool design and welding parameters and process conditions used. Oosterkamp et al., [4] identified that the role of tool pin in the friction stir welding, the tool pin is to shear the material to its back side during translation of the tool and the inserted rotating pin brings the material at both sides of the joint line to the plastic state, aided by frictional heat input of the shoulder.

Figs. 3–5 show the effect of tool pin profile on tensile strength of friction stir welded AA6061 aluminium alloy. Of the five joints, the joints fabricated by square pin profiled tool exhibiting highest tensile strength irrespective of welding parameters. Next to square pin profile, triangular pin profiled tool showing almost matching tensile properties to that of square pin followed by threaded, taper and straight cylindrical pins, respectively.

The relationship between the static volume and swept volume decides the path for the flow of plasticized material from the leading edge to the trailing edge of the rotating tool. This ratio is equal to 1 for straight cylindrical, 1.09 for tapered cylindrical, 1.01 for threaded cylindrical, 1.56 for square and 2.3 for triangular pin profiles [15]. In addition, the triangular and square pin profiles produce a pulsating stirring action in material flow. The square pin profile produces 80 pulses/s and triangular pin profile produces 60 pulses/s in case of AA6061 at a speed of 1200 rpm. Moreover, the eccentricity of the lobes of the square and triangular pins assisting the breaking up of the oxides of the metal resulted in superior tensile properties. Though the ratio of the swept volume of the triangular pin is higher than the square pin profile, better tensile properties of square pin profile is due to increased number of pulses/s for the given speed.

5. Conclusions

- A mathematical model has been developed to predict the tensile strength of friction stir welded AA6061 aluminium alloy joints by incorporating welding parameters and tool profiles using statistical tools such as design of experiments, analysis of variance and regression analysis.
- The joints fabricated using square pin profiled tool with a rotational speed of 1200 rpm, welding speed of 1.25 mm/s and axial force of 7 kN exhibited superior tensile properties compared to other joints.

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